Step 3

Equation 27 gives
$S_{min} \cong (4\ Y_{DO}^2/\{\sin[(45^\circ + \theta)/2]\})^{1/2} \cong 3$ m (10 ft)
From Figure 8, at $X_D = 0$, $h_u = Y_U - Y_{\theta U} = 3.6$ m (11.9 ft), and $\theta_u = 21.8^\circ$, Equation 28 gives
$S_{max} \cong (4\ h_u^2/\{\sin[(\theta_u + \theta)/2]\})^{1/2} \cong 12$ m (40 ft)
Use trial drain spacings S = 4.6 m (15 ft), 9.2 m (30 ft), and 13.7 m (45 ft).

Step 4. Phreatic Surface M

See columns 11 and 12 of Figure 8 for the solution for S = 4.6 m (15 ft). Similar analyses were made for S = 9.2 m (30 ft) and S = 13.7 m (45 ft). The resulting phreatic surfaces are plotted in Figure 3.

CONCLUSIONS

1. A method of estimating phreatic surfaces at the midway profile between parallel drains is introduced. Because of the large number of assumptions made in the derivation of practical mathematical analyses, the results must be considered approximate only.
2. The analysis procedure can be based on flow-net analysis or on a completely mathematical analysis. Using the mathematical analysis has the advantage in that it can be computerized by using the procedure from Figure 8 for an infinite-slope seepage source.
3. For a typical problem, the analysis procedure resulted in a range of drain spacings from 4.6 to 13.7 m (15-45 ft), which coincides well with the range commonly used in practice.
4. Further study is needed to define the optimum cross-sectional spacing to use in the analysis of a given drain spacing S. The analysis is sensitive to the cross-sectional spacing used. Using a wider spacing (ΔX in Figure 8) between cross sections results in a greater predicted drawdown. An optimum cross-sectional spacing (ΔX) as a function of drain spacing (S) is expected and needs to be verified by model study and experience.

REFERENCES

1. H. R. Cedergren. Seepage, Drainage, and Flow Nets. Wiley, New York, 1967, pp. 94-98 and 334-344.
2. W. V. Jones and R. Larsen. Investigation and Correction of a Highway Landslide. Proc., 8th Annual Idaho Engineering Geology and Soils Engineering Symposium, Pocatello, 1970, pp. 123-144.
3. T. C. Kenney, M. Pazin, and W. S. Choi. Design of Horizontal Drains for Soil Slopes. Journal of Geotechnical Engineering Division, Proc., ASCE, Vol. 103, No. GT11, Nov. 1977, pp. 1311-1323.
4. R. W. Prellwitz. Analysis of Parallel Drains for Highway Cut-Slope Stabilization. Proc., 16th Annual Idaho Engineering Geology and Soils Engineering Symposium, Boise, 1978, pp. 153-180.
5. A. Casagrande. Seepage Through Dams. In Contributions to Soil Mechanics, 1925-1940, Boston Society of Civil Engineers, 1963, pp. 295-336.
6. M. E. Harr. Groundwater and Seepage. McGraw-Hill, New York, 1962, pp. 52-54 and 64-69.
7. J. N. Luthin. Drainage Engineering. Krieger, Huntington, NY, 1973, pp. 149-169.
8. J. Wesseling. Subsurface Flow into Drains: Vol. 2—Drainage Principles and Applications. International Institute for Land Reclamation and Improvement, Wageninen, Netherlands, 1973, pp. 1-56.

Publication of this paper sponsored by Committee on Subsurface Drainage and Committee on Environmental Factors Except Frost.

Evaluation of Pavement Systems for Moisture-Accelerated Distress

S. H. Carpenter, M. I. Darter, and B. J. Dempsey, Department of Civil Engineering, University of Illinois, Urbana

The occurrence of moisture-accelerated distress (MAD) caused by poor internal drainage in a pavement is predictable after examining components of the pavement and its environment. MAD is defined as any distress primarily caused or accelerated by moisture. A fast, inexpensive method for identifying existing and potential MAD has been developed and provides a valuable tool to the maintenance engineer managing a system of pavements and the design engineer evaluating a single pavement for possible rehabilitation. In the procedure for evaluating MAD the following are done: Extrinsic and intrinsic factors are predicted, the condition of the pavement surface is surveyed, and the pavement is tested. Each of these is considered a level of refinement in determining the occurrence of MAD in the pavement system and represents increased cost. The extrinsic factors in level one are concerned with climatic influences on the moisture state of the pavement. The intrinsic factors are examined for likelihood of internal drainage problems caused by the materials and cross section being used. This provides an index of potential MAD problems. In the condition survey any existing distress on the pavement surface is directly measured. The final step is to conduct physical tests of the pavement, if it is felt that inadequate information has so far been obtained. This testing may be either destructive or nondestructive. By the final evaluation stage, one has sufficient working knowledge to make an accurate judgment as to the existence of or the potential for occurrence of MAD. One or more alternative maintenance and rehabilitation strategies can be selected, based on the evaluation results, to reduce or prevent MAD. The final selection of the alternative is based on the present condition of the pavement, traffic level, economics, and future requirements.

The data presented in this paper are part of an evaluation manual developed for field use by pavement engineers. The manual provides complete descriptions of how to identify pavements with poor internal drainage that potentially could deteriorate prematurely. Four distinct components have been examined that show a relationship to moisture-accelerated distress (MAD): extrinsic factors, intrinsic factors, condition survey, and testing.

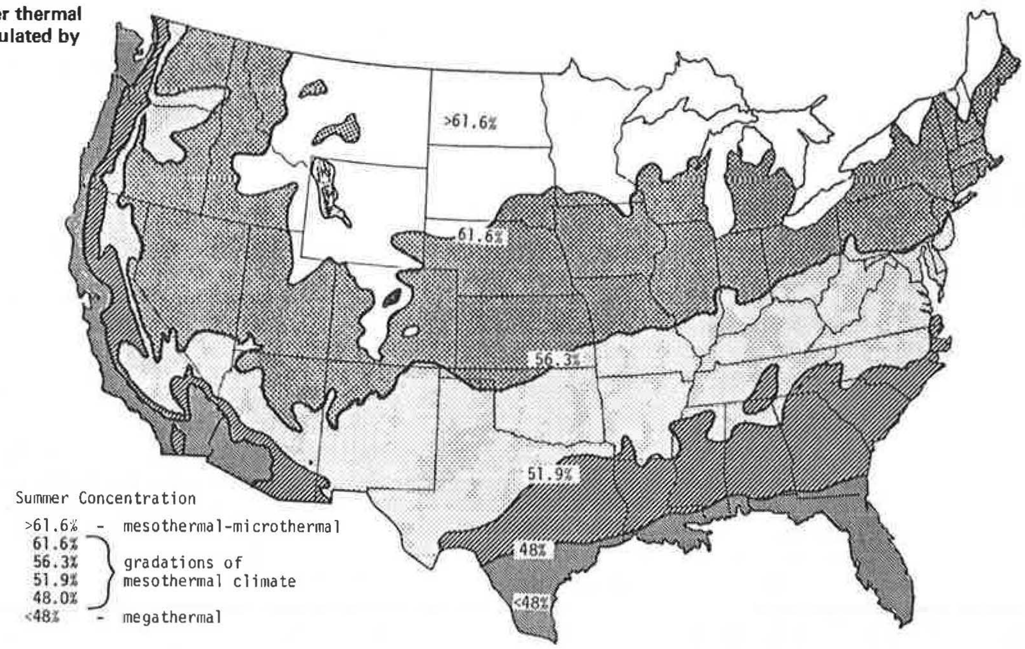
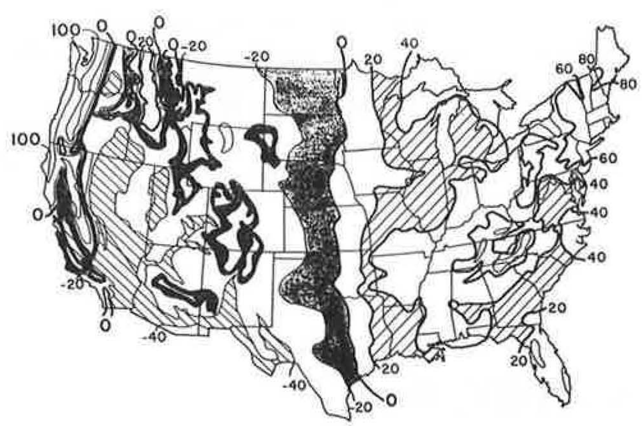


Figure 1. Summer thermal gradations as calculated by Thornthwaite.

Figure 2. Distribution of Thornthwaite moisture index.



Extrinsic factors, those that influence the moisture condition in the pavement, primarily are climatic factors. The intrinsic factors represent the internal properties of the pavement that influence the moisture condition, including pavement type and material. The condition survey directly measures any existing distress on the pavement surface, which allows the condition and existing MAD to be determined. The testing may be either destructive or nondestructive and is used when the results from the first three are inconclusive concerning moisture presence.

These factors follow a logical sequence in determining, with a minimum of work, the potential that MAD has of occurring in a pavement or the possibility that MAD is responsible for the damage existing in the pavement. They represent a means of estimating the degree of MAD and can indicate what maintenance should or should not be done.

DEVELOPMENT

Extrinsic Factors

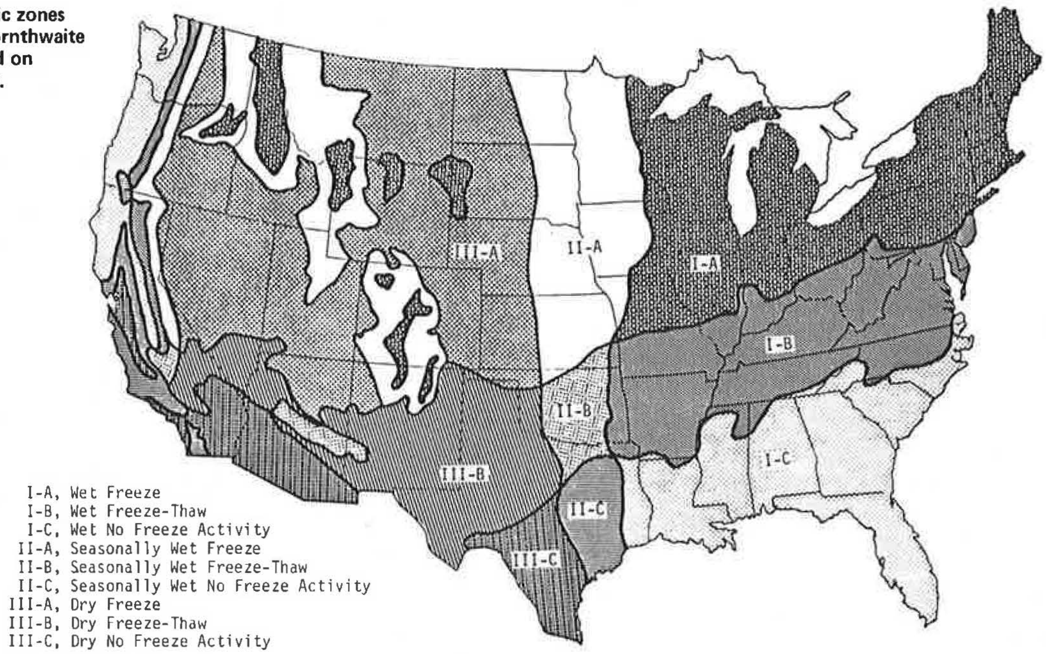
Extrinsic factors are the external factors that influence the moisture and its behavior. Climate is the major extrinsic factor that alters the moisture in a pavement system and causes the moisture to behave poorly. Temperature of and moisture in the soil are the two major climatic variables. The Federal Highway Administration currently recognizes four climatic zones (1). The north-south dividing line represents the mean freezing index value of 100, the east-west dividing line the point where yearly annual rainfall equals the yearly annual evaporation. As far as they go, these delineations do differentiate areas of different pavement performance. But they do not provide a means of differentiating within each zone on a rational basis.

To accurately identify the influence of climate on a pavement, it is necessary to have an accurate, if only relative, description of that climate. The major climatic classification schemes include the Koeppens (2) and the Thornthwaite classification schemes (3).

The Thornthwaite procedure is the only one that allows calculation of gradations in the numerical values. The same values that indicate relative moisture transport can also be used to indicate the relative severity of the winter. The Thornthwaite classification scheme uses the concept of potential evapotranspiration, or the amount of moisture that would leave the soil through evaporation and transpiration if there were an unlimited supply of water to the soil system. Obviously the more energy (heat) that reaches the earth's surface, the more water that will be removed. This is the indicator of winter severity: a comparison of the amount of potential evapotranspiration that accumulates in the three summer months with that of the total for the year. The greater the percentage the more severe the winter. Potential evapotranspiration does not occur when the temperature drops below 32°F (0°C).

Although there are doubts about the accuracy of the proposed calculation procedure used to estimate potential evapotranspiration (2), the scheme, which uses these numbers to delineate climate, is sound and has been found easier to apply than the more complicated energy-balance techniques. By comparing monthly rainfall with the monthly values of potential evapotranspiration, one may obtain indications of surplus or deficit moisture in the soil. The yearly balance is the

Figure 3. Climatic zones derived from Thornthwaite calculations based on material behavior.



moisture index of wetness and dryness in the soil.

The distribution of the summer thermal concentrations is shown in Figure 1 (3). The Thornthwaite moisture index is shown in Figure 2. These quantities allow for a continuous gradation between different climatic zones, which is far preferable to setting upper and lower bounds with no allowance for variation between them.

The climatic zones shown in Figure 3 were obtained from correlations with moisture and deformation studies and temperature influences. Each zone indicates an area where similar pavements will generally receive similar climatic inputs and thus perform similarly in terms of pavement structure (intrinsic factors). The following Roman numerals indicate the moisture regions and corresponding connotations: I—subgrade saturated all year and all soils generally illustrating poor performance characteristics unless stabilized; II—definite seasonal wet and dry periods shown in subgrade and performance varying greatly with the season and locale; III—subgrade generally very dry with little or no moist period and good performance exhibited by nearly all soils commonly used. The capital letters refer to the temperature regimes and corresponding connotations: A—severe winters, extremely low temperatures with high potential for frost damage in the subgrade; B—moderate winters with high potential for freeze-thaw activity throughout the winter extending deep into the base course; C—mild winters with some freeze-thaw cycling in surface course in north to high temperature stability problems in summer over entire region.

The map in Figure 3 illustrates areas of equal potential for moisture in the pavement system, regardless of the intrinsic factors. Obviously, if there is a high water table, performance will worsen. This is one of the items considered in the intrinsic analysis in the next section. The first step for the engineer is to determine which climatic zone he or she is in. The map given in Figure 3 should suffice for most locations, but the manuals provide procedures for numerical calculations when the engineer feels something other than a long-term average is needed to indicate the existing climatic conditions.

Intrinsic Factors

Intrinsic factors are those existing in the pavement or those built into it. With a given set of extrinsic factors, as previously discussed, the intrinsic factors will determine how water will behave and what the potential for MAD will be. The important intrinsic factors are

1. Pavement type,
2. Base and subbase drainability,
3. Subgrade drainability, and
4. Existing drainage.

Pavement type determines whether the base course will be exposed to a large or a small amount of water infiltrating through joints and cracks. The degree of infiltration, however, is dictated by the condition of the pavement and even more by the drainage capability of the base or subbase material. These will cause initial rapid removal of water entering by surface infiltration. If these materials build up high saturation values over a long period, permanent deformations may become excessive and pumping will develop at an accelerated rate.

The ability of a granular material to absorb or release water is a function of grain size, permeability, density, and other properties. The complexity of moisture flow, particularly unsaturated flow, has been demonstrated by Dempsey and Elzeftawy (4) in their mathematical model for moisture flow in pavements. This model is far too complicated to use for the initial study of potential moisture problems but is ideally suited for drainage analysis on a more refined level.

The ability of a pavement to absorb or drain water is the limiting factor for moisture entering through surface cracking. The ability of a crack to pass moisture is far greater than that of all but the most open-graded bases with little or no fines content (5).

The U.S. Army Corps of Engineers has used a procedure to estimate the time it takes to drain a saturated base-course drainage layer to a given percentage of the total amount that can possibly drain by gravity (6). This procedure requires that 50 percent

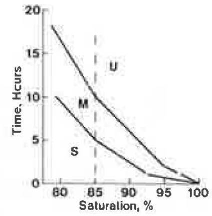


Figure 4. Drainability curves for granular base material.

of the amount of water that can be removed must be removed within 10 days (7). This criterion was developed for airfield pavements where loading is not as frequent as it is for highways. For proper drainage in a highway application the time limit should be reduced appreciably. Another factor that must be considered is that draining half the water in a specified time does not take into account the actual moisture state of the material. A concrete sand may lose only 3 percent (by volume) of its water under gravity drainage, while a pea gravel may lose 40 percent. At the end of the specified time the sand will have a much higher saturation level and will exhibit decreased performance compared to the pea gravel. The reader is referred to the manuals for the actual calculation process (8, 9).

The critical saturation level has been established as 85 percent. This is a point where repeated loading damage increases drastically for granular materials (10). The desired time to reach this saturation has been determined as between 5 and 10 h. Figure 4 illustrates the criteria developed for granular material (8). These curves can be developed from

1. Roadway geometry,
2. Permeability estimate,
3. Effective porosity estimate, and
4. Gradation and percent fines.

A material classified as unacceptable will not flow water readily and in a wet climate will not have enough time to drain before another rainfall. This material would tend to remain above the critical saturation level. A marginal material will have slightly less fines and tend to remain nearer the critical saturation level.

The subgrade material also will experience moisture problems. The degree of severity will vary depending on texture, topography, and water-table depth. These factors are important in the agricultural classification of soils because they directly influence the drainage characteristics of the soil. Hole (11) used this classification for soils and applied a numerical value for each classification, which he termed the natural drainage index (NDI). It varies from -10 for an "excessively drained" i (good) soil to +10 for a "very poorly drained" k (poor) soil. The drainage terminology is readily available on most soil maps, and, although different from engineering terminology, it does describe the drainability of the subgrade material. This description can be used to indicate the relative ability of a subgrade to hold water.

Frequent changes in soil make the application of this indicator a very approximate procedure. In studies on concrete roads, Haas (12) showed very good relationships among the NDI, deterioration, and maintenance required. This indicator can, then, indicate where moisture is most likely to cause problems in a pavement, although the extent of the problems caused by the soil variation cannot be determined. NDI can be used to indicate areas where drains may be effective, according to soil conditions.

A subgrade was assumed to be impermeable when the drainability time for the granular layers was developed. If the subgrade is good it will aid the granular layer by providing vertical drainage to the water table, and marginal drainability will be altered to an acceptable level. If the subgrade is poor it cannot assist in draining the granular layer, and its performance will be low as indicated by Haas (12) and will produce accelerated distress. An intermediate subgrade will not aid the granular layer, nor will it have excessively poor performance.

Surface Condition

The extrinsic and intrinsic analysis will indicate the extent to which moisture problems may develop, but the surface condition points to the extent to which moisture has actually damaged the pavement. The type, amount, and severity of distress present are necessary to accurately describe the overall condition of the pavement. The presence of particular distress types, or their absence, can indicate the presence or absence of MAD.

The distress that is present can be examined with the classification indicated from the extrinsic and intrinsic analyses. The following situations could arise for a given pavement.

1. If only minor distress exists, the rate of deterioration will depend on the level of moisture predicted by the extrinsic and intrinsic evaluation. The higher the rating, the faster the deterioration and the sooner maintenance or rehabilitation needed.
2. If significant distress exists, this may or may not indicate moisture damage, depending on what distress is present. Moisture-related distress indicates maintenance or rehabilitation is needed (a) immediately if in a wet area, (b) soon if in a seasonally wet area, or (c) in the future if in a dry area.

Distress must be defined by type, severity, and quantity. Extensive research work has been recently accomplished in the development of distress-identification manuals for streets, airfields, and highways (9, 14, 16). This development required extensive field surveys in many parts of the United States and discussions with many engineers working in pavement evaluation, maintenance, and rehabilitation. Numerous training sessions have been held with field maintenance personnel to ensure that the definitions are practical and easy to use.

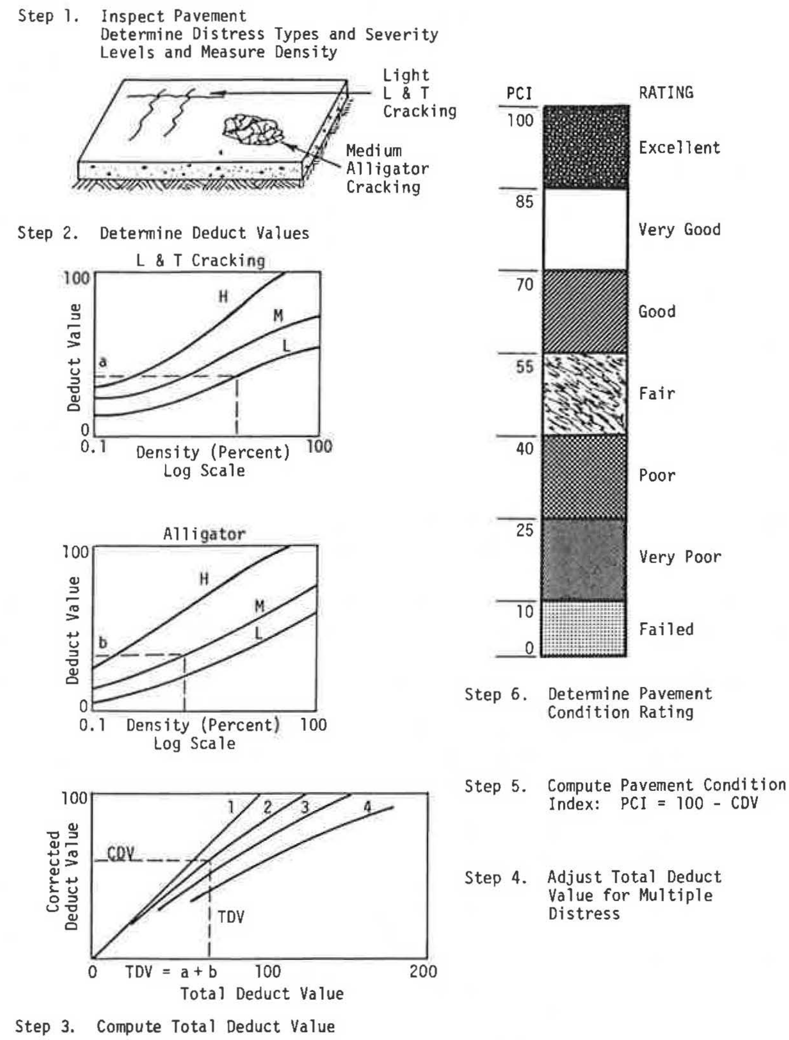
A composite pavement distress index, developed by Shahin and others (13, 16), combines the types, severities, and quantities of distress into a single value for any given pavement section. This was accomplished by defining a pavement condition index (PCI) as follows:

$$PCI = 100 - \sum_{i=1}^{p} \sum_{j=1}^{m_i} a(T_i, S_j, D_{ij})\, F(t, q) \qquad (1)$$

where

- $a(\ )$ = deduct value depending on distress type T_i, level of severity S_j, and density (or quantity) of distress D_{ij};
- i = counter for distress types;
- j = counter for severity levels;
- p = total number of distress types for pavement type under consideration;
- m_i = number of severity levels for the ith type of distress; and

Figure 5. Steps to calculate the pavement condition index for a street.



$F(t, q)$ = an adjustment function for multiple distresses that vary with total summed deduct value (t) and number of deducts (q).

Deduct-value curves for each distress type and severity level were determined based upon the composite judgment of a large group of experienced pavement engineers. Thus, the calculated PCI of a given pavement section represents the overall engineering judgment of a large group of experienced engineers as to the pavement's structural integrity (protection of the investment, maintenance needs) and surface operational condition (user-related consideration). The steps necessary to determine the PCI for a given street are summarized in Figure 5. The procedure is very simple and straightforward, has been officially adopted by the U.S. Air Force, and is under trial implementation by other agencies.

The PCI rating deduct values can be used to indicate the distress condition that is related to moisture damage. A MAD index can be defined as the percentage of deduct values caused or accelerated primarily by moisture. The severity of this index will indicate how far developed moisture damage is and the rate at which further deterioration may be expected to develop. Combined with the extrinsic and intrinsic analysis, both the PCI and the MAD index can indicate the efficacy of installing drainage, performing maintenance, or reconstructing at the present time or in the immediate future (8).

Testing

A testing program is the final step in the analysis procedure and should be considered only when the previous three factors produce anomalous results. When moisture damage is predicted from extrinsic and intrinsic analyses but the condition index does not show any moisture damage, the properties of the pavement system must be investigated. The same must be done if there is extensive moisture damage, but the intrinsic and extrinsic factors indicate that no moisture problems should exist. Samples may have to be taken to the laboratory for testing, or the testing may be done in situ.

The major variables influencing the intrinsic analysis will be the moisture-related properties of the base, subbase, or subgrade. As such, the properties that might need to be determined will include

1. Gradation,
2. Clay content (type of fines),
3. Permeability,
4. Moisture content, and
5. Deformation characteristics.

These properties can be determined from laboratory tests of disturbed and undisturbed samples. The permeability and deformation characteristics require undisturbed samples for laboratory testing. This can be quite expensive and impractical for the level of analysis conducted in this study. The more suitable approach would be to conduct an in situ permeability test (15) and appropriate deflection measurements of the pavement and shoulder. These tests, with gradation, mineral data, and moisture content, would indicate whether the intrinsic analysis based on original properties was in error and by what amount.

Given the additional data provided by the testing, a new intrinsic analysis will provide a new classification that is a better indicator of the moisture-related condition of the pavement.

APPLICATION

The four areas of analyses briefly presented here have been more fully explained in a series of manuals prepared for the Federal Highway Administration as a part of the subdrainage and shoulder rehabilitation project. These manuals detail the data used in constructing each procedure to obtain a true indication of the moisture influence on the pavement. The first two manuals present the research background for moisture and distress, respectively, and the third, which contains the procedures, is the manual to be used by the field and maintenance engineers to evaluate their pavements.

The evaluation manual contains step-by-step procedures that allow field personnel with a minimum of training to complete a MAD analysis. The person performing the extrinsic analysis may locate the pavement on a series of climatic maps. If he or she chooses he or she can use available climatic data from monthly weather bulletins and can calculate the variables for the desired number of years. The calculations for years the pavement has been in service will provide an indication of the actual moisture the pavement has been exposed to. For longer time in service, the moisture values will be closer to the long-term average values used to construct the maps. This analysis provides a climatic indicator that relates the severity of moisture available to the pavement itself.

The intrinsic analysis requires knowledge of the type of base or subbase material and the subgrade material. The base course is analyzed to determine its potential for retaining moisture. The subgrade is classified as to its drainability, from soil maps where possible. The combination of these two material classifications provides an indicator of the potential a pavement has to hold water and thus to increase the potential for moisture damage. When the extrinsic and intrinsic factors are combined, an indicator or potential MAD is formed where potentially available moisture is combined with moisture-sensitive materials. Using general descriptions of the expected behavior of the materials, the evaluator will have a physical description of the material in the pavement. This provides a clearer understanding of the expected behavior.

The distress-condition survey produces two numerical indices that are related to the overall condition (PCI) and the extent of moisture-related damage that has occurred in the pavement (MAD). The evaluator follows a step-by-step procedure to examine the pavement section under question and to determine the condition indices. The evaluator then enters a table in which the condition indices allow statements to be made concerning the present and future condition of the pavement.

Using these tables, the evaluator can obtain physical descriptions of his or her pavement section along with explanations relating the current state of the pavement to expected moisture damage in the future. Recommendations can be made concerning maintenance, rehabilitation, and use of subdrainage to alter the growth of moisture-related distress. The maintenance recommendations are coordinated with the results of a part of the overall project that determines what warrants subdrainage. That portion of the study requires more in-depth material property determination than is necessary for development of the manual presented in this paper. The general implications that are described in this surficial analysis are backed up quite well by the more detailed analysis.

SUMMARY

A manual has been prepared that allows an evaluator who has minimum experience or training to analyze a pavement section and determine whether the distress present is moisture related and if so to what extent. This field manual examines the potential for moisture-accelerated damage from the following viewpoints:

1. Extrinsic, or external, climatic influences;
2. Intrinsic, or internal, material properties;
3. Condition index, or the extent of moisture-related distress; and
4. Testing, or the use of tests to examine conflicting results.

By following a step-by-step procedure the evaluator will determine a number of moisture-related facts about the particular pavement section under investigation. Among these facts are

1. Origin of moisture problems caused by (a) climate or (b) a particular material in the base or subgrade;
2. Extent of moisture problems;
3. Usefulness of subdrainage in retarding deterioration; and
4. Recommendations for maintenance and rehabilitation.

ACKNOWLEDGMENT

Support for the project was provided by the Federal Highway Administration, Office of Research and Development. We are grateful for the technical coordination provided by George W. Ring III, contract manager.

The opinions, findings, and conclusions expressed are ours and not necessarily those of the Federal Highway Administration or the U.S. Department of Transportation.

REFERENCES

1. M. I. Darter. Design of Zero-Maintenance Plain Jointed Concrete Pavement: Vol. I—Development of Design Procedures. Federal Highway Administration, Rept. FHWA-RD-111-77, 1977.
2. H. J. Critchfield. General Climatology, 3rd Ed. Prentice-Hall, Englewood Cliffs, NJ, 1974.
3. C. W. Thornthwaite. An Approach Toward a Rational Classification of Climate. Geographical Review, Vol. 38, No. 1, 1948, pp. 55-94.
4. B. J. Dempsey and A. E. Elzeftawy. Moisture Movement and Moisture Equilibria in Pavement Systems. Univ. of Illinois, Urbana, Interim Rept. IHR-604, 1976.
5. B. F. McCullough, A. Abou-Ayyash, R. W. Hudson, and J. D. Randall. Design of Continuously Reinforced Concrete Pavements for Highways. NCHRP Project 1-15, Final Rept., 1975.
6. W. E. Strohm, Jr., E. H. Nettles, and C. C.

Calhoun, Jr. Study of Drainage Characteristics of Base Course Materials. HRB, Highway Research Record 203, 1967, pp. 8-28.
7. E. S. Barber and C. L. Sawyer. Highway Subdrainage. HRB, Proc., Vol. 31, 1952, pp. 643-666.
8. S. H. Carpenter, M. I. Darter, and S. Herrin. A Pavement Moisture Accelerated Distress (MAD) Identification System. Vol. I. Federal Highway Administration (in preparation).
9. M. I. Darter and S. Herrin. Pavement Distress Identification Manual. Vol. II. Federal Highway Administration (in preparation).
10. A. J. Haynes and E. J. Yoder. Effects of Repeated Loading on Gravel and Crushed Stone Base Course Materials Used in the AASHO Road Test. HRB, Highway Research Record 39, 1963, pp. 82-96.
11. F. D. Hole. Suggested Terminology for Describing Soils as Three-Dimensional Bodies. Soil Science Proc., Vol. 17, No. 2, 1953, pp. 131-135.
12. W. M. Haas. Drainage Index in Correlation of Agricultural Soils With Frost Action and Soil Performance. HRB, Bull. 111, 1955, pp. 85-98.
13. M. Y. Shahin, M. I. Darter, and S. D. Kohn. Development of a Pavement Maintenance Management System: Vol. I—Airfield Pavement Condition Rating. U.S. Air Force Civil Engineering Center, Tindall Air Force Base, FL, Technical Rept. AFCEC-TR-76-27, Dec. 1976.
14. M. Y. Shahin, M. I. Darter, and S. D. Kohn. Development of a Pavement Maintenance System: Vol. II—Airfield Pavement Distress Identification Manual. U.S. Air Force Civil Engineering Center, Tindall Air Force Base, FL, Technical Rept. AFCEC-TR-76-27, Dec. 1976.
15. U. L. Maytin. A New Field Test for Highway Shoulder Permeability. HRB, Proc., Vol. 41, 1962, pp. 109-124.
16. M. Y. Shahin, M. I. Darter, and S. D. Kohn. Development of a Pavement Condition Index for Roads and Streets. U.S. Army Construction Engineering Research Laboratory, Champaign, IL, Interim Rept. M-232, May 1978.

Publication of this paper sponsored by Committee on Subsurface Drainage and Committee on Environmental Factors Except Frost.

Influence of Precipitation, Joints, and Sealing on Pavement Drainage

Barry J. Dempsey, Department of Civil Engineering, University of Illinois, Urbana
Quentin L. Robnett, School of Civil Engineering, Georgia Institute of Technology, Atlanta

A study was conducted to determine the influence of precipitation, joints, and sealing on drainage of concrete pavements. Detailed drainage studies were conducted on four pavement test sections. Two jointed concrete pavement test sections were located on I-85 near Atlanta, and one continuously reinforced concrete pavement test section and one reinforced jointed concrete pavement test section were located on I-57 near Champaign, Illinois. Subsurface drainage was installed on the Georgia test pavements as part of the test preparation. Subsurface drainage on the Illinois test pavements had been installed previously as part of a shoulder rehabilitation program. All drainage outflows were measured by specially designed flowmeters capable of continuously monitoring volumes. All precipitation data were obtained on an hourly basis from weather stations near the pavement test sites. Analysis of data indicated that pavement drainage outflow was significantly related to precipitation. It was also found that the edge joint was a major factor contributing to water infiltration into pavement systems. Edge-joint sealing was found to reduce water infiltration in the jointed concrete pavement test sections in both Georgia and Illinois. Edge-joint sealing on the continuously reinforced section in Illinois did not significantly reduce surface infiltration. No measurable drainage outflow was observed on the completely sealed pavement test section in Georgia.

Water is a fundamental variable in most problems associated with pavement construction, design, behavior, and performance. Moisture usually has very significant effects on pavement systems because the structural section and subgrade are often susceptible to large variations in moisture content and are strongly influenced by surrounding climatic conditions.

The problem of water in pavements has long been of concern to engineers. Cedergren and O'Brien (1) have listed over 225 abstracts of pertinent literature on the subject of subdrainage. Recently Dempsey and others (2) completed a state-of-the-art review of the existing literature on and current practices for subdrainage, shoulder structures, and maintenance of pavement systems for the Federal Highway Administration.

Methods for controlling moisture in pavement systems can generally be classified in terms of protection through the use of waterproofing membranes and anticapillary courses, the use of materials insensitive to moisture changes, and water evacuation by means of subdrainage. Ridgeway (3), Ring (4), Woodstrom (5), and Barksdale and Hicks (6) have all reported on the problem of water infiltration through cracks and joints of concrete pavements and have indicated that the performance life of many concrete pavements could be extended by improved protection and drainage of the structural section. Darter and Barenberg (7) have indicated that protection of the structural pavement section and subgrade by adequate sealing of joints and cracks can help prolong pavement life.

Although water-related distress is obvious in pavement systems, few studies have been conducted to determine the pavement conditions that contribute to water problems and the procedures that will best mitigate these problems. Ridgeway (3) and Barksdale and Hicks (6) have conducted controlled field tests to determine the percentage of surface water infiltrating into pavement systems. Ridgeway (3) measured infiltration rates for both portland cement concrete and asphalt concrete pavements in Connecticut. Barksdale and Hicks (6) conducted tests at two Georgia Interstate locations that have plain jointed portland cement concrete traffic lanes and asphalt concrete shoulders. These studies have indicated that